PROBING BLACK HOLE SPIN ORIENTATIONS
THE INNER DISK INCLINATION ANGLE IN GRO J1655-40

Zuzana Turonova,[1,2,3] Greg Salvesen,[1,2] and Katherine McGowan[4,2]

[1] XCP-8, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA.
[2] Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
[3] Silesian University in Opava, Institute of Physics, Na Rybníčku 626/1, 746 01 Opava, Czech Republic.
[4] ISR-1, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA.

Introduction and background

A spin-orbit misalignment is an angular momenta misalignment between a spinning black hole and its binary orbit, as shown in Figure 1. Spin-orbit misalignments have important implications for understanding black hole spin measurements, accretion disk dynamics, close binary evolution, supernova kicks, and compact object mergers. Spin-orbit misalignments are proving more common than previously appreciated, but they are difficult to constrain.

The spin-orbit misalignment angle is accessible in a black hole (BH) X-ray binary (XRB) system. The binary orbital inclination angle measurement follows from well-understood techniques (e.g., ellipsoidal variations, eclipses). But what about the BH spin orientation? Conventional theory predicts that the BH spin axis is parallel to both the jet axis and the rotational axis of the X-ray emitting inner disk region. If true, then both the jet inclination angle i_{jet} and the inner disk inclination angle i_{disk} offer an observational tracer of the BH spin inclination angle $i_\bullet$.

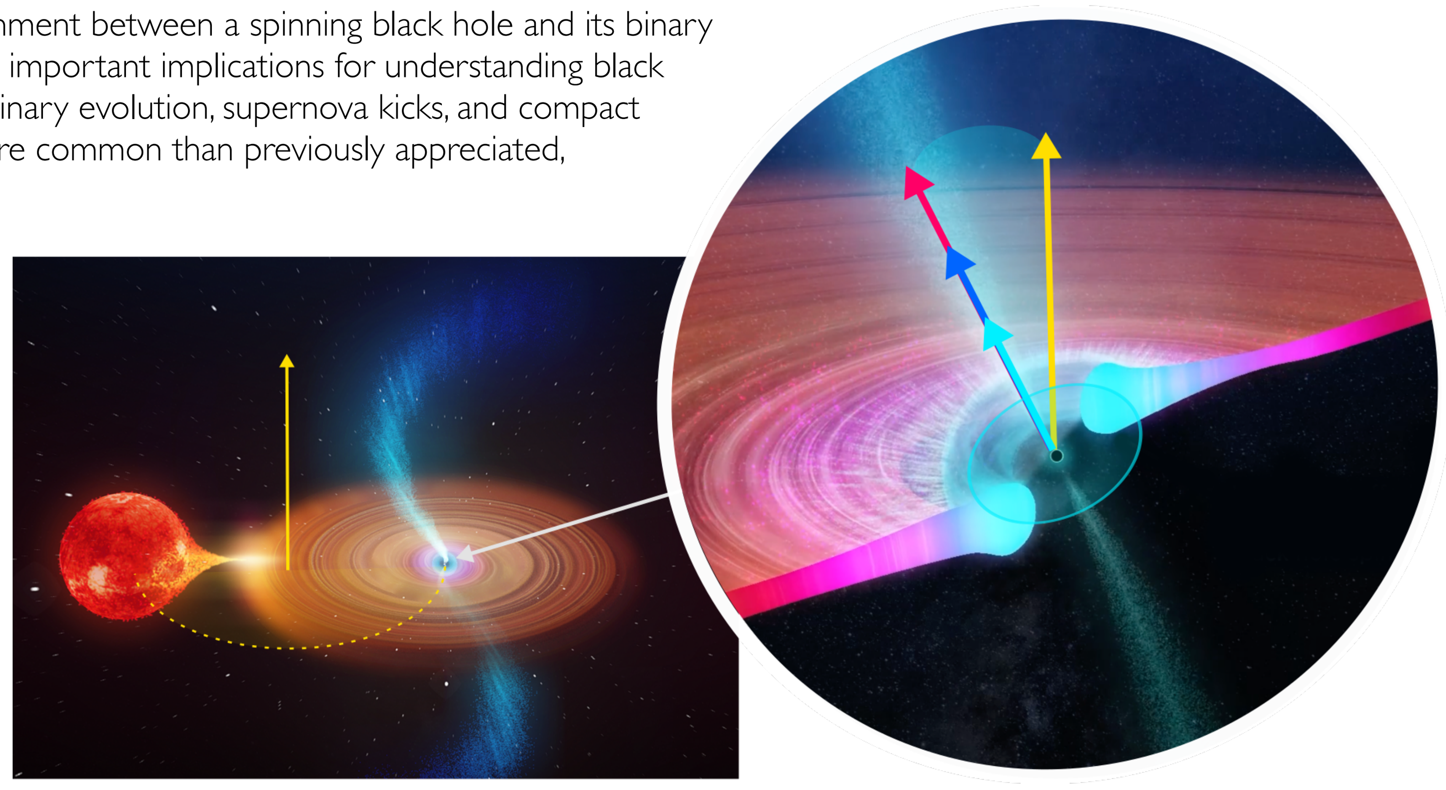

Fig 1: A representative BH XRB with a modest misalignment between the binary orbit and the BH spin angular momenta. The BH spin axis, jet axis and rotational axis of the inner accretion disk flow are all aligned as predicted by conventional theory. Credit: ICRAR

OBJECTIVES:

Our goal is to measure the inner disk inclination angle i_{disk} in the BH XRB GRO J1655–40 by repurposing the disk continuum fitting technique, typically used to measure BH spin. This will allow us to test the expectation of disk-jet alignment and independently verify the spin-orbit misalignment in the system.

[1] For all the models hereafter see [4]: https://heasarc.gsfc.nasa.gov/xanadu/xspec/XspecManual.pdf

Disk continuum fitting technique

There are two established techniques for measuring BH spin in X-ray binaries: disk reflection fitting and disk continuum fitting. The former models the relativistically broadened iron emission line feature in the disk reflection spectrum [1], and the latter models the accretion disk continuum emission [2]. Both approaches identify the inner disk radius with the innermost stable circular orbit (ISCO), which maps to the BH spin.

The disc continuum fitting method applies to BH XRBs in high-luminosity ($L \sim 0.1\, L_{Edd}$) soft spectral states. It approximates the specific flux emitted by the disk as a color-corrected, multi-temperature, blackbody model for a geometrically thin, optically thick accretion disk [3].

In practice, this disk continuum model can constrain only two free parameters. For models like `kerrbb`[1] these parameters are typically chosen to be the mass accretion rate $\dot{M}$ and the BH spin $a_\bullet$. By fitting the observed thermal continuum spectrum with this model, one can obtain the spin of a BH by measuring the inner disk radius r_{in} from known parameters: BH mass $M_\bullet$, distance $D_\bullet$, inner disk inclination i_{disk} and color-correction factor f_{col}.

Disk continuum fitting practitioners usually assume that the inner disk aligns with the binary orbit, but this may not be correct.

Microquasar GRO J1655-40

A microquasar is a BH XRB that emits relativistic jets. The microquasar GRO J1655–40 (hereafter J1655) has well-known system parameters, as required for a disk continuum fitting analysis. The jet inclination angle $i_{jet} \simeq 85^\circ$ follows from a kinematic model for symmetric jets, given proper motions of the approaching and receding ejecta [5] and the source distance $D = 3.1^{+0.4}_{-0.6}$ kpc [6]. The black hole mass $M_\bullet = 6.3 \pm 0.5\, M_\odot$ and binary orbital inclination angle $i_{orb} = 70^\circ.2 \pm 1^\circ.9$ come from modeling elliptical variations of the donor star [7]. Together, the measurements $i_{jet} \simeq 85^\circ$ and $i_{orb} = 70^\circ.2 \pm 1^\circ.9$ imply a spin-orbit misalignment angle $> 15^\circ$ [8].
Although J1655 system parameters are well-constrained, its BH spin magnitude is contentious. The disk continuum fitting spin $a_\bullet = 0.7 \pm 0.1$ [9] is at odds with the spin $a_\bullet > 0.9$ found from disk reflection fitting [10].

Data reduction

The Neil Gehrels Swift Observatory (hereafter Swift[2]) observed the 2005 outburst of J1655 [11]. We reduce 5 of these observations obtained by the X-ray telescope (XRT) operating in Windowed Timing (WT) mode. During all 5 observations, the source was in the high/soft state and exhibited low temporal variability.

Both photon pile-up[3] and dust-scattering halos[4] can affect the extracted spectrum. We compare the detector intensity profile to the in-flight calibrated WT-mode point spread function (PSF) to confirm the presence of photon pile-up and dust scattering emission (Fig. 2).

To eliminate these effects, we develop an analysis pipeline that extracts the appropriate region of the PSF and models the dust-scattered emission.
We use the grades ratio diagnostic[5] to determine the extent of the affected PSF core, which we omit when extracting spectra (Fig. 3).

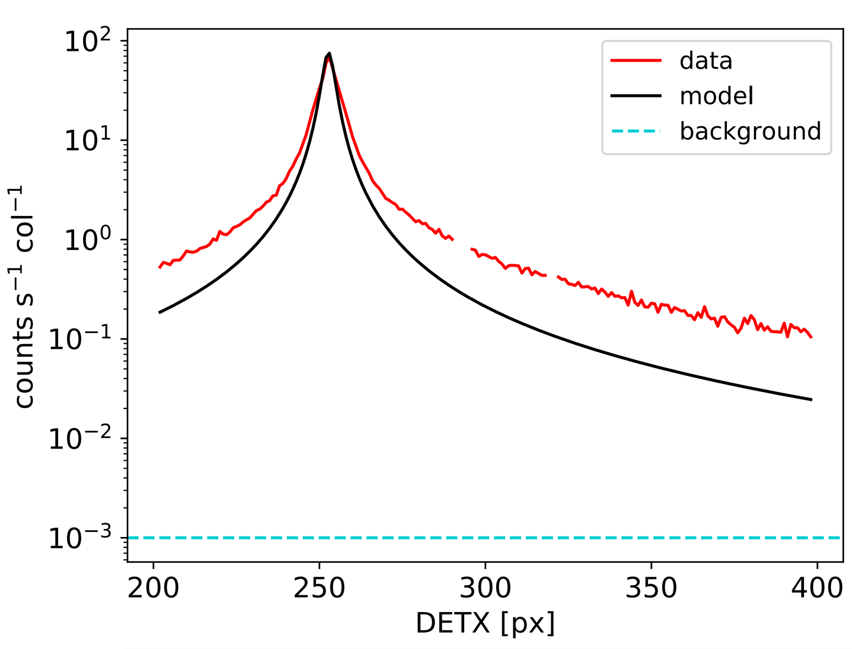

Fig 2: Detector intensity profile (red) compared to the in-flight calibrated WT-mode PSF (black). The effects of photon pile-up and dust-scattering emission are visible in the slight decrement in the core and the excess in the wings respectively.

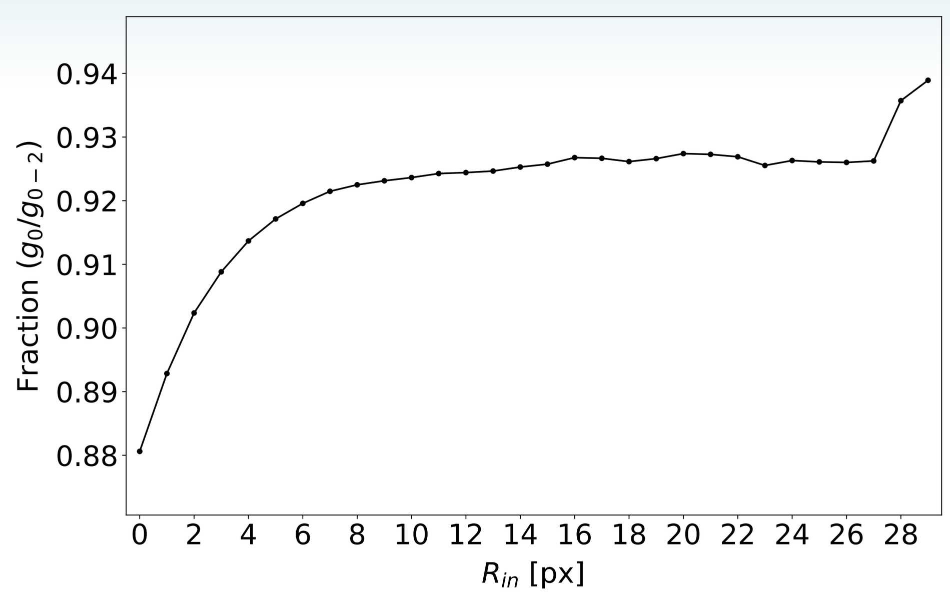

Fig 3: Grades ratio plot showing the fraction of events classified with grade 0 against inner exclusion region of radius R_{in} for one of the observations. Constant fraction of grade 0 events implies little pile-up, whereas the turnover at $R_{in} \sim 8$ px signifies the piled-up region radius suitable for exclusion.

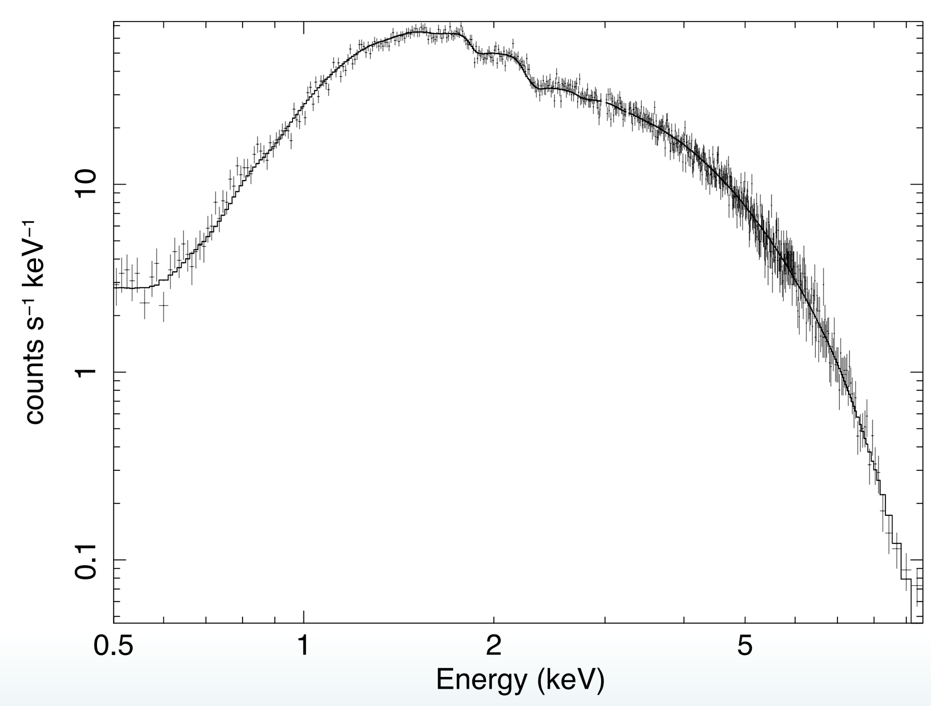

Fig 4: Best-fit using the `TBabs×kerrbb` model.

[2] See https://www.swift.ac.uk/

[3] High count rate can cause the CCD to register two low-energy photons as one high-energy photon.

[4] The interstellar dust scatters source photons onto detector-bound trajectories - ring-like structures around the source are visible.

[5] See https://www.swift.ac.uk/analysis/xrt/pileup.php

Spectral fitting

We start our spectral analysis by fitting each of the five spectra with the model `TBabs×diskbb` in `Xspec`. After exploring whether the data require a Comptonizing component such as `powerlaw`, `simpl` or `compTT`, we conclude that the absorbed disk model `TBabs×diskbb` alone is sufficient to describe the data. We then replace the `diskbb` model with the more physical model `kerrbb`.

We investigate the effect of the dust-scattering on the spectra using a dust-scattering model `xscat` along with both `diskbb` and `kerrbb` models. We conclude that the dust-scattering component does not drastically influence the best-fit parameters as shown in Table 1.

Our χ^2 approach to fitting each Swift/XRT dataset with a `TBabs×kerrbb` model can realistically constrain only two free parameters (see Table 1). This is a consequence of the featureless nature of disk-continuum models, which can be described by only two parameters: a flux amplitude and a photon energy translation.

Therefore, to constrain the unknown system parameters $a_\bullet$ and $\dot{M}$, we adopt a physically-motivated f_{col} value of 1.7 [12] while freezing i_{disk} to either the jet inclination angle or the binary orbital inclination angle. All the other `kerrbb` parameters are held fix. Both disk inclination angles give good fits, but using $i_{jet} \simeq 85^\circ$ requires an unreasonably high mass accretion rate ($L \sim 62\,\%\, L_{Edd}$). Setting more than 2 parameters free does not give good constrains on their values. We present these results in Table 1.

$a_\bullet$	$\dot{M}$ $[10^{18}\, g/s]$	N_H $[10^{22}\, /cm^2]$	i_{disk} [°]	χ^2/ν
`TBabs×kerrbb`				
$0.852^{+0.010}_{-0.009}$	0.93 (3)	1.03 (2)	70.2	1.0686
0.45 (2)	$5.49^{+0.19}_{-0.20}$	0.92 (2)	85	0.9786
$0.45^{+0.05}_{-0.01}$	$5.49^{+0.40}_{-0.72}$	0.92 (2)	$> 84.39^a$	0.9800
`TBabs×xscat×kerrbb`				
0.81 (1)	1.12 (4)	$0.72^{+0.05}_{-0.01}$	70.2	0.9630
$0.42^{+0.04}_{-0.06}$	$5.74^{+0.45}_{-0.32}$	$0.70^{+0.03}_{-0.02}$	85	0.9540
$< 0.86^a$	$3.46^{+1.80}_{-1.64}$	$0.69^{+0.08}_{-0.02}$	$81.71^{+2.44}_{-5.27}$	0.9583

Table 1: Results from a dataset fitting with `TBabs×kerrbb` model (upper segment) and `TBabs×xscat×kerrbb` model (lower segment) using a χ^2 approach for one of the five Swift/XRT observations. We fix the black hole mass $M_\bullet = 6.3\, M_\odot$, distance $D = 3.1$ kpc and choose the inner disk inclination i_{disk} to be either the binary orbital inclination $i_{orb} = 70^\circ.2$, the jet axis inclination $i_{jet} = 85^\circ$, or leave it free. We adopt the value of color correction factor $f_{col} = 1.7$ and present best-fitted values of BH spin $a_\bullet$, mass accretion rate $\dot{M}$ and column density N_H with their $90\,\%$ uncertainties. We include the chosen disk inclination i_{disk} and resulting fit statistics χ^2/ν.

[a] Parameter values pegged at their hard limit during error calculations, implying $i_{disk} > 84.39^\circ$ and $a_\bullet < 0.86$ respectively.

Conclusions and future work

At this stage of our work, further analysis is needed. We can conclude that there is no strong preference for favoring either the jet inclination $i_{jet} \simeq 85^\circ$ or the binary orbital inclination $i_{orb} = 70^\circ.2$.

To test the expectation of disk-jet alignment and independently verify the spin-orbit misalignment in J1655 we will pursue a Markov chain Monte Carlo (MCMC) analysis that incorporates informative priors. Our expectation is that an MCMC approach will better explore the full parameter space to simultaneously constrain three parameters: i_{disk}, $a_\bullet$ and $\dot{M}$.

To hopefully improve statistical uncertainties, we plan to jointly fit all five observations. To better understand the systematic uncertainty associated with the choice of disk continuum model, we plan to fit the data using `bhspec` model.

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